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Study of nighttime ionization over the equator in the altitude range of 150-200 km during magnetically disturbed period

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Abstract : Theoretical decay of nighttime ionization over the equator has been calculated and these results are compared with the rocket measurements of Goldberg *et al* (1974) at Thumba (magnetic lat. 0.5 °N) during a magnetically disturbed period. Comparison reveals that the normal nighttime ionization by scattered He I and He II radiations is not adequate to maintain the ion densities at the observed level during a magnetically disturbed period over the equator. The source of additional ionization has been investigated and identified as the energetic particles from the ring current in the energy range of 1 to 100 kev.

Keywords : Magnetic activity, ion composition, drift, energetic particles, ring current.

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1. Introduction

After sunset, the electron density in the altitude range of 150-200 km is maintained at a relatively high level in the night even in the absence of direct solar radiation and it has a positive correlation with the geomagnetic activity. The phenomenon of nighttime ionization and its magnetic activity dependence have been studied by various workers (Ogawa and Tohmatsu 1966, Fujitaka *et al* 1971, Wakai 1971, Smith *et al* 1974, Shen *et al* 1976, Voss and Smith 1980). However, most of these studies were carried out for mid and high latitudes. There has been no noteworthy effort in this direction for the equatorial zone of Indian subcontinent. In this paper, an attempt has been made to study theoretically the decay of ionization in the altitude range of 150-200 km at the equator during a magnetically disturbed night and these theoretical results are compared with those obtained by Goldberg *et al* (1974) from the rocket experiments conducted over Thumba, an equatorial station in India. Goldberg *et al* (1974) carried out two ion composition measurements from about 100 to 150 km, one at 19 : 38 LMT on 9.3.70 and the other one at 1 : 08 LMT on 10.3.70. They also deduced the soft energy particle flux in the energy range of 1 to 20 kev from the data of the second flight. A moderate magnetic storm preceded the day of rocket launch and k_p varied between 4 and 6 on the launch date. We have studied the decay of ionization of NO^+, O_2^+ and O^+ ions after sunset for different production rates at two representative altitudes, 150 and 200 km by solving time-dependent continuity equation for each ion. Goldberg *et al* (1974) have also derived *F*-region drift and its time variation from ionograms obtained on the same night at Thumba and pointed out that this drift was not expected to be important below 200 km. In view of this, we have ignored the effect of drift in our calculations for 150 km. We have started the computation at 19 : 38 LMT with the experimental ion densities of the first flight as initial values and continued upto 1 : 08 LMT, the time of the second flight. The comparison of the theoretical and experimental results at 1 : 08 LMT reveals the following feature.

For 150 and 200 km, the normal nighttime ionization by scattered He I and He II radiations is not sufficient to maintain the ion densities at the observed level and it is necessary to invoke an additional ionization source to explain the experimental results. The nature of this source has been investigated and it is concluded that the additional ionization in this altitude range over the equator during a magnetically disturbed night is due to the energy deposition by energetic particles (1 to 100 kev range) originating from the ring current.

2. Theoretical calculation

The reactions controlling the ion chemistry of the *E*-region are given below (Thomas 1982).

Reaction	Rate co-efficient ($cm^3\ S^{-1}$)
1. $O_2^+ + e \rightarrow O + O$	$K_1 = 2.10 \times 10^{-7} \left(\frac{300}{T}\right)^{0.7}$
2. $NO^+ + e \rightarrow N + O$	$K_2 = 4.4 \times 10^{-7} \left(\frac{300}{T}\right)^{1.2}$
3. $O^+ + O_2 \rightarrow O_2^+ + O$	$K_3 = 2 \times 10^{-11}$
4. $O^+ + N_2 \rightarrow NO^+ + N$	$K_4 = 1 \times 10^{-12}$
5. $O_2^+ + NO \rightarrow NO^+ + O$	$K_5 = 4.5 \times 10^{-10}$
6. $O_2^+ + N \rightarrow NO^+ + O$	$K_6 = 1.8 \times 10^{-10}$
7. $N_2^+ + O \rightarrow NO^+ + N$	$K_7 = 1.5 \times 10^{-10}$

8. $N_2^+ + O_2 \rightarrow O_2^+ + N_2$ $\quad K_8 = 4 \times 10^{-11}$

9. $N_2^+ + O_2 \rightarrow NO^+ + NO$ $\quad K_9 = 1 \times 10^{-14}$

The production (Q) and loss (L) functions of NO^+, O_2^+ and O^+ ions are listed below

$$Q(NO^+) = q(N_2^+) + K_4[O^+][N_2] + K_5[O_2^+][NO] + K_6[O_2^+][N]$$
$$L(NO^+) = K_2[NO^+][N_e]$$
$$Q(O_2^+) = q(O_2^+) + K_3[O^+][O_2]$$
$$L(O_2^+) = K_5[O_2^+][NO] + K_6[O_2^+][N] + K_1[O_2^+][N_e]$$
$$Q(O^+) = q(O^+)$$
$$L(O^+) = K_4[O^+][N_2] + K_3[O^+][O_2]$$

in which q's represent the production rates of the appropriate ions resulting from photoionization.

The appearance of $q\,(N_2^+)$ in the expression of $Q(NO^+)$ is due to the rapid transfer of N_2^+ to NO^+ through eqs. (7) and (9).

The number densities of O_2 and N_2 are taken from CIRA (1972) and those of NO and N are obtained from Strobel *et al* (1976). The nighttime photoionization of N_2, O_2 and O above 140 km are mainly by scattered He I and He II radiations and their ionization rates (denoted by q_n) are adopted from Fujitaka *et al* (1971). We have done two sets of calculations in the present study —(i) with the ionization rates q_n and (ii) with the enhanced ionization rates (q_e) required to bring reasonable match between the theoretical results and experimental ion densities at 1 : 08 LMT. Table 1 shows the values of q_n and q_e for different ions at 150 and 200 km.

Table 1. Ionization rates for different ions at 150 km and 200 km.

Production rates in $cm^{-3}\,S^{-1}$	150 km			200 km		
	$q\,(NO^+)$	$q\,(O_2^+)$	$q\,(O^+)$	$q\,(NO^+)$	$q\,(O_2^+)$	$q\,(O^+)$
q_n	0.19	0.055	0.035	0.3	0.035	0.14
q_e	1.0	1.2	0.5	0.3	0.14	1.6

Time-dependent continuity equations of ions NO^+, O_2^+ and O^+ for q_n and q_e are solved by using Runge-Kutta method. Results of comparison between these theoretical results and experimental ion densities are discussed in the next section. As already mentioned, we have incorporated the *F*-region ion drift as given by Goldberg *et al* (1974) in our calculation for 200 km only. The drift data reveals that the drift became very small from 23 : 00 LMT onwards and it was virtually zero at the time of the second flight at 1 : 08 LMT. In order to calculate the divergence term in the continuity equation, we have assumed that the height gradients of the ions vary linearly with time between those obtained from the height profiles measured during the first and second flights.

3. Results and discussion

Figures 1-3 show the theoretically computed decay of ionization of NO^+, O_2^+ and O^+ at 150 km for q_n and q_e along with the measured ion densities at 1 : 08 LMT. Figures 4-6 show the similar results at 200 km. It is seen from the above figures that for the production rate q_n, the theoretical ion densities at both the heights are lower than the observed ones at 1 : 08 LMT. A reasonable match between the theoretical and experimental results is obtained when q_e is used in our calculations.

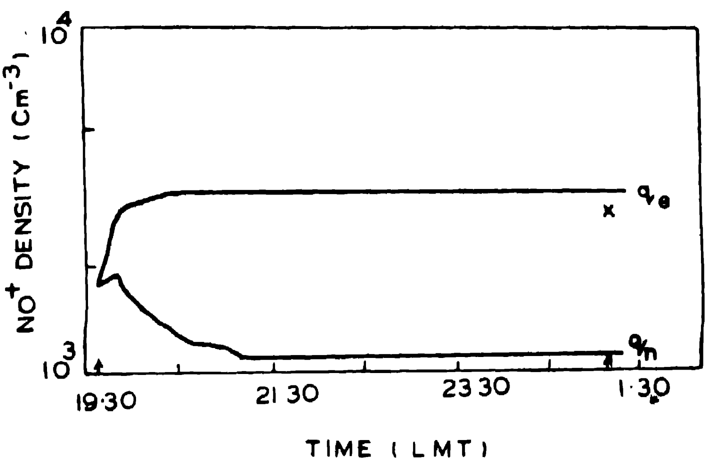

Figure 1. Theoretical variation of NO^+ with time at 150 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (×).

The above results confirm that the normal nighttime ionization by He I and He II radiations is not sufficient to maintain the ion densities at the level observed at 1 : 08 LMT during a magnetically disturbed night at the equator. Additional ionization rates $(q_e - q_n)$ needed to achieve a reasonable agreement with the experimental ion densities at 150 and 200 km are 2.42 $cm^{-3}S^{-1}$ and 1.57 $cm^{-3}S^{-1}$ respectively. We now proceed to investigate the nature of this additional nighttime ionizing source at this altitude range.

Positive correlation of the nighttime electron density at low latitudes in the altitude range of 150 to 200 km with the geomagnetic activity is now well established (Wakai 1971, Shen *et al* 1976, Voss and Smith 1980). Energetic particle precipitation as a possible cause of this enhanced ionization was first suggested by Hirao *et al* (1965). After the discovery of energetic ions trapped near the equator at low (~ 400 km) altitudes (Moritz 1972, Mizera and Blake 1973) and subsequent investigations by several workers (Prolss 1973, Lyons and Richmond 1978, Tinsley 1978, Voss and Smith 1980) it is now confirmed that the energetic particles in the energy range of 1 to 100 kev are present in a zone of ± 20° centred on the magnetic equator and that they have an intensity variation similar

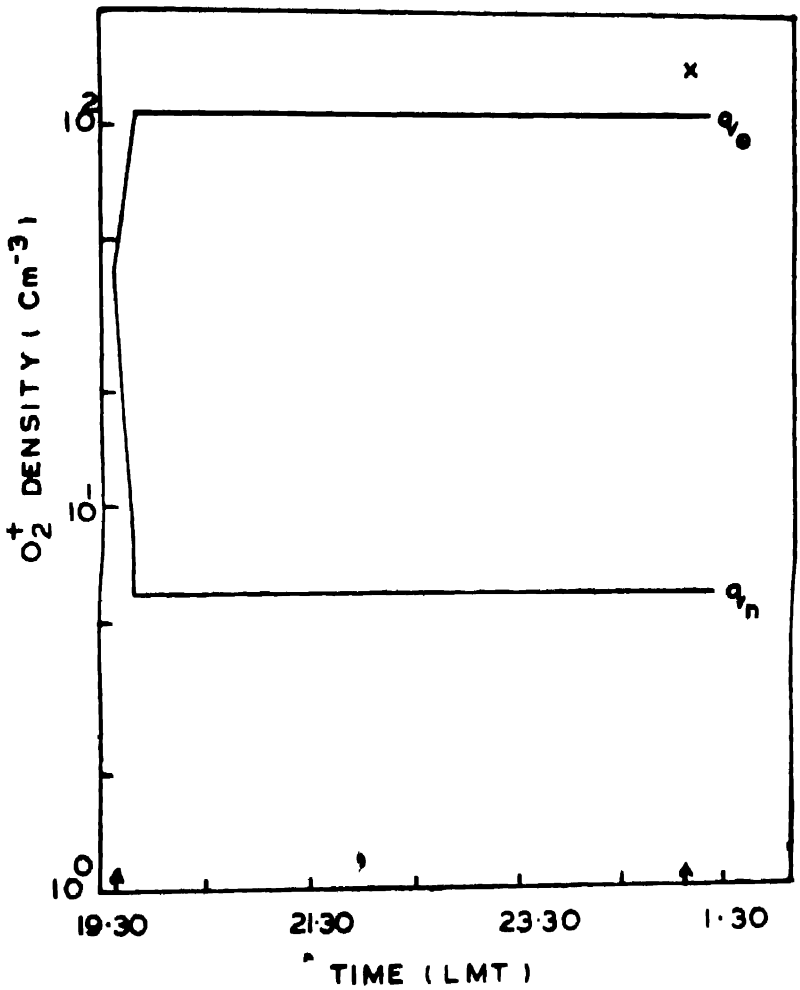

Figure 2. Theoretical variation of O_2^+ with time at 150 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (×).

to that of the ring current. Further, these energetic particles contribute significantly to nighttime ionization above 150 km at the equator particularly during a magnetically disturbed period. In view of this, the most likely candidates for the additional ionization in our study are the energetic particles (1 to 100 kev range) depositing the energy into the atmosphere.

We now proceed to carry out the calculation of ionization rate due to this energy deposition over the equator. Prolss (1973) carried out systematic theoretical

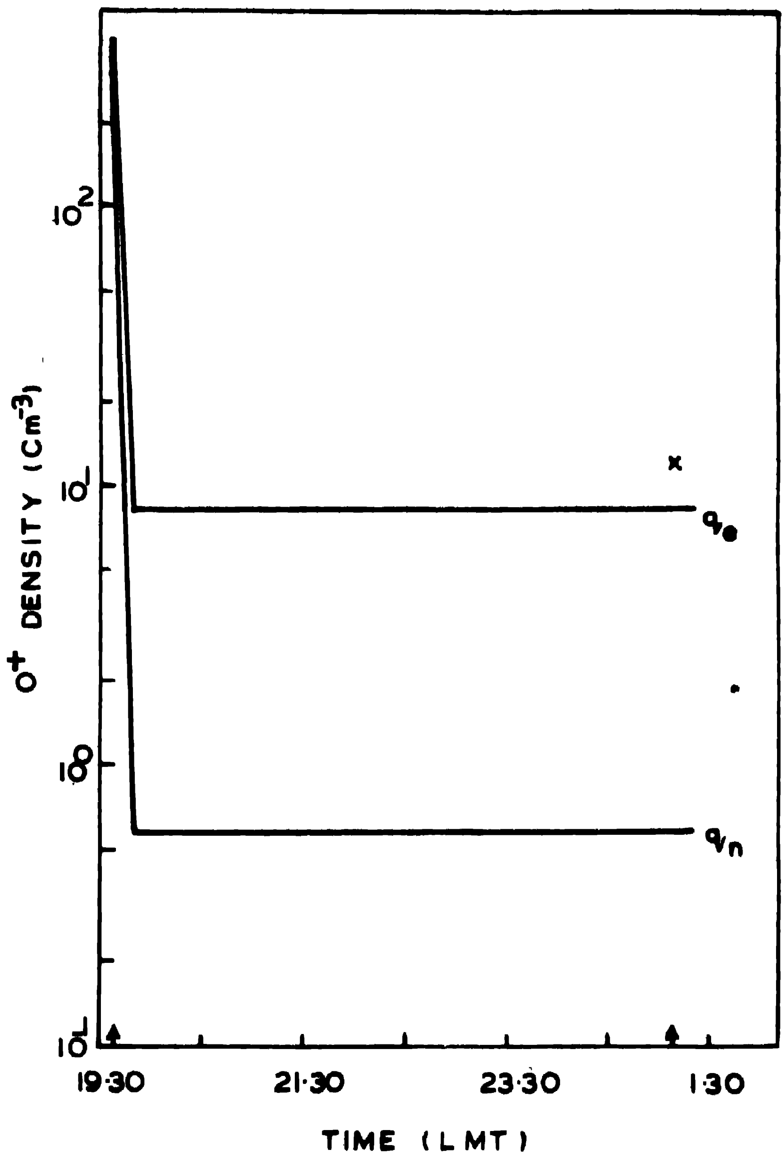

Figure 3. Theoretical variation of O^+ with time at 150 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (x).

investigation to calculate the energy deposition into the ionosphere from neutralized ring current particles as a function of latitude and altitude. Lyons and Richmond (1978) made use of the experimental results of energetic particle measurements by

Mizera and Blake (1973) and did the ionization rate calculation in the line of Prolss's analysis over Arecibo (magnetic latitude 30) 36 hours into the storm

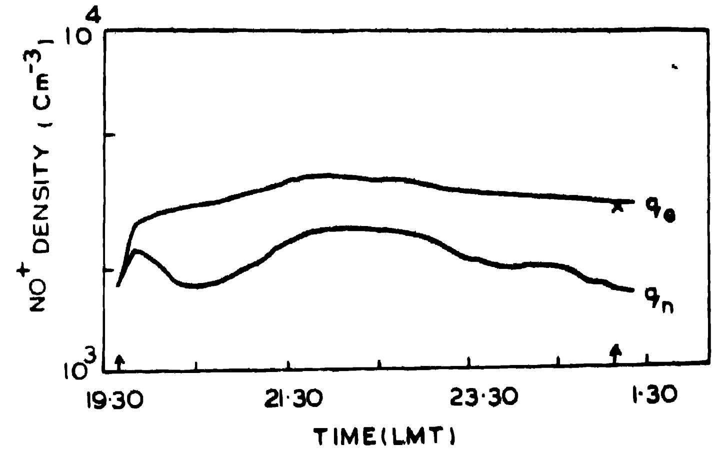

Figure 4. Theoretical variation of NO^+ with time at 200 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (×).

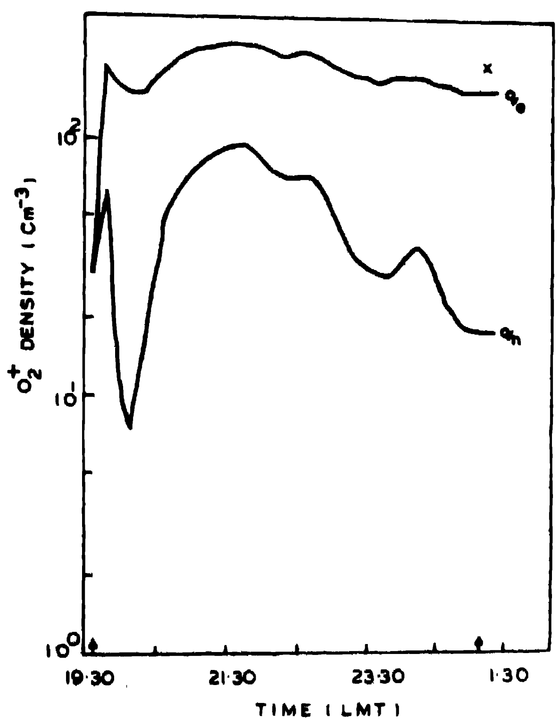

Figure 5. Theoretical variation of O_2^+ with time at 200 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (×).

recovery phase. We would follow similar analysis for the ionization rate estimation over the equator during a magnetically disturbed period.

Goldberg (1974) observed an energetic particle flux (1 to 20 keV energy range) of $10^7/cm^2$ sec. ster at 200 km during the rocket flight at 1.08 LMT on 10.3.70. It would have been ideal to calculate the ionization rate from the above data. But due to the absence of informations regarding the particle flux beyond 20 kev

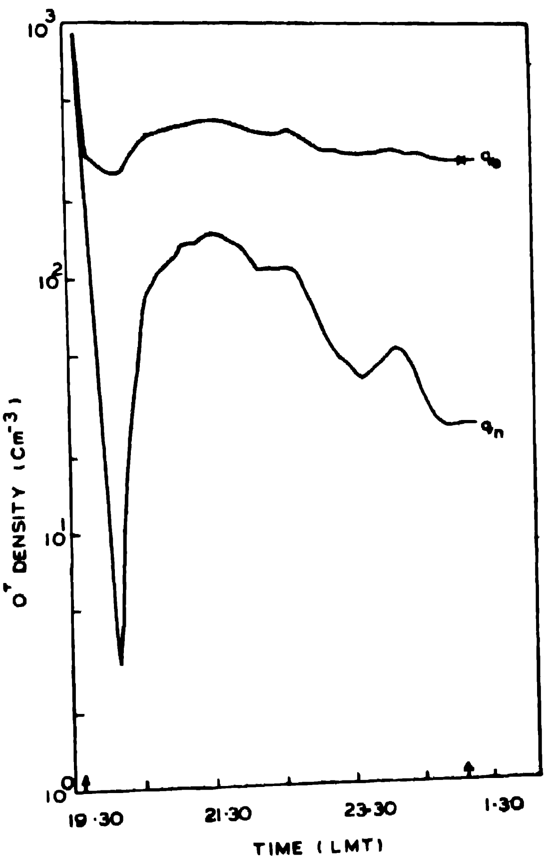

Figure 6. Theoretical variation of O^+ with time at 200 km. Arrows indicate the rocket launching times. The observed values of ion densities at 1 : 08 LMT also shown (×).

and the energy spectrum of the flux, such exercise is not feasible. Therefore, we turn to the data of Mizera and Blake (1973) obtained under similar geomagnetic conditions. Lyons and Richmond (1978) derived from the above data the column production rate over Arecibo as 6×10^6 per cm^2 column sec. According to Tinsley (1978) the column production rate at the equator is almost twice of that at Arecibo. Therefore, the column production rate over the equator will be 12×10^6. Letting the energy to be deposited over a range of 50 km (150-200 km) in altitude, we get an average ionization rate $\sim 2.4\ cm^{-3}\ S^{-1}$. This value is very nearly equal to the production rates used in our calculation. However, it should be pointed out that the magnetic storms have large variabilities and the observations of Mizera and Blake (1973) may not quantitatively represent the energetic particle precipitation over the equator on the night of the rocket experiment by Goldberg *et al* (1974). Yet it is clear from the above calculations that an ionization rate of about $2.4\ cm^{-3}\ S^{-1}$ over the equator due to the energetic particles is not unlikely during a magnetically disturbed night. It is necessary to conduct at the equator, simultaneous measurements of ion composition and densities, scattered He I and He II radiations, energetic particle flux and its energy spectrum and probably vertical drift during quiet as well as magnetically disturbed nights for detailed study of this phenomena.

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